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THERMOREGULATORY RESPONSES IN THE COLD:EFFECT OF AN EXTENDED COLD WEATHER CLOTHING SYSTEM (ECWCS)

by

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ABSTRACT

This report addresses the human thermoregulatory responses of wearing a new cold-weather system [ECWCS] at rest or during exercise. The ECWCS (insulation= 3.6 clo; weight=10.1 kg) encompasses skin- tight polypropylene underwear, polyester/cotton fatigues, polyester-insulated liners, balaclava, vapor-barrier boots, and polytetrafluroethylene [PTFE]-lined outer garments. Six fit males each rested (M= 71 $W \cdot m^{-2}$) and did treadmill exercise (speed 0.98 $m \cdot s^{-1}$, M= 171 $W \cdot m^{-2}$) while wearing different handwear with the ECWCS; the handwear included: a light duty glove (LD, clo = 0.86), heavy duty glove (HD, clo= 1.05), or an Arctic mitten (clo= 1.46). Cold exposures were at T_a = 0 °C, -20 °C, and -30 °C, rh = 20 %rh, wind speed = 1.34 $m \cdot s^{-1}$. A maximal 120 min cold challenge for each soldier was designated (based on physiological safety measures) as a maximal endurance time [ET,min]. All experiments were on separate days. Rectal (T_{re}), middle finger, and mean weighted skin ($\bar{T}_{sk}$, 10 sites) temperatures were recorded continuously; oxygen uptake and heart rate were measured periodically and total body weight loss (m_{sw}, g/h) was determined after each run. During the rest experiments: at 0 °C, the ECWCS maintained T_{re} at 37 °C for the maximal ET with all handwear configurations;for each lower ambient condition, steady-state T_{re} dropped -0.2 °C per each 10 °C decrease in T_a. For the most part, middle finger temperatures at or near 5 °C prior to the maximal ET were the basis for premature attrition; 10- site $\bar{T}_{sk}$ of 29.4 °C was associated with subjective thermal discomfort. Excessive m_{sw} (~280 g h^{-1}) and maintenance of body temperatures (T_{re} =37.6 °C and $\bar{T}_{sk}$ =≤ 29.4 °C) showed that the ECWCS was over-adequate at the extreme exercise/cold stress levels studied in this experiment. A multiple correlation analysis demonstrated that ET could be predicted adequately by finger temperature, absolute metabolism, rectal and 10-site skin temperatures. Effect of sweating during exercise reduced the effective thermal insulation of the ensemble thereby lowering the ET's for each handwear item. The Arctic mitten rendered the highest ETs during rest or exercise. The ECWCS should tender adequate endurance times in cold-dry ambients provided that ventilation and removal of extra layers is allowed as an easy option during heavy exercise so that thermal insulation is not excessively decreased by body moisture. Keywords cont'd on DD1473

INTRODUCTION

A. BACKGROUND

The Extended Cold Weather Clothing System (ECWCS) was developed in an attempt to have on hand a universal ensemble which is functional in cold-wet or cold-dry environments (-51 °C), acts to improve the water vapor permeabilities to thermal insulation potential, and yet reduces the load bearing items for the individual soldier. At least seven agencies contributed to the joint working group (JWG) giving input towards a final acceptance of this ensemble. These agencies included the US Army Training and Doctrine Command (TRADOC), the US Army Infantry School (USAIS), the US Army combined Arms Center (CAC), the Marine Corps Development and Education Center (MCDEC), the US Army Development and Employment Agency (ADEA), The US Army Natick Research Development and Engineering Center (NRDEC). The Military Ergonomics Division of the US Army Research Institute of Environmental Medicine (USARIEM) contributed significantly to the JWG towards the ascertainment of the thermal insulation and evaporative potential of this system. During the developmental periods of the system, this Division evaluated up to ten different prototype versions for their thermal insulative (clo value, I_T) and evaporative properties (i_m/clo). In these initial studies, the thermal insulative values of the prototypes ranged from 3.42 to 3.83 clo. The evaporative potential compared to the thermal insulation ranged from 0.11 to 0.13 (Table I). Although the thermal insulative properties are variable, the evaporative potential is similar among the different prototypes.

The ECWCS uses the layering concept (2,3,4,7,21,29), under the assumption being that by adding or removing clothing items, in consideration of a soldier's metabolic activity

and climatic conditions, the individual is able to thermoregulate optimally. The person therefore prevents any body overheating or overcooling by adjustment of the specific clothing layers. Typically issued ECWCS items consist of the following:

a) The innermost layer of the ECWCS consists of polypropylene which purportedly (15,22) allows the transmission of water vapor (produced by insensible perspiration or active sweating) from the skin to the next layer and then to the outermost layer. This consists of a long sleeve turtleneck undershirt and long underwear of expedition weight polypropylene;

b) The next clothing layer uses a 100% polyester fiber pile as a bib-overall and pull-over cardigan which, albeit highly hydrophobic (9,15), is a loose weave that was not designed as an outer garment;

c) The third layer from the skin consists of the standard Temperate Battle Dress Uniform (TBDU) composed of 50% nylon/50 % cotton twill fabric (thermal insulation of 1.49 clo im/clo of 0.26). Included in this layer are trousers and a "bush"-type coat.

d) The next layer of the ECWCS includes modified versions of the US Army M6S field jacket and trousers liners. The latter are insulated with fine-filament (4 oz per yard), polyester batting;

e) The outermost layer of the ECWCS incorporates a hooded parka and trousers of nylon coated with poly-tetra-fluoroethylene (PTFE) laminated fabric (Gore-Tex®).

After extensive wear trials in 1985, this system was type classified for use and issued to special operations and light infantry units (9,21). Also issued with the ECWCS are the standard white vapor barrier boots and the arctic trigger-finger mittens. Specific improvements to the mobility and thermal characteristics of handwear items continue as a problem in the

cold because of the reduced circulatory heat flow, presence of arterio-venous anastomosis, and geometry present in the extremities (26,27,28) contrary to the overall insulation and circulatory control exhibited at other sites of the body surface. Also still uncertain to date is the efficacy of state-of-the-art materials used in the manufacture of gloves in rendering sufficient cold-weather protection with the ECWCS (15,22,23).

B. PURPOSE

The present study was designed to define an operative range of temperatures for specific handwear items which could be suitably used with the ECWCS and provide effective cold weather protection. This is the first quantitative experimental study to investigate thermal biophysical and human responses to mild cold stress with this system.

2. METHODS and PROCEDURES:

a. Handwear items. Three standard-issue US Army handwear systems were used in this study. All handwear were procured from military stocks and were in new, unused condition. The handwear evaluated with the ECWCS consisted of :

1) the standard US Army Light Duty Work Glove with a five-finger woolen insert, designated as LD. This glove was separately evaluated on the USARIEM copper hand model (see US-1 paper in this conference proceedings) and had a thermal insulation value of 0.86 clo (0.13 $m^2 \cdot K \cdot W^{-1}$);

2) the standard US Army Heavy Duty Work Glove with a five-finger woolen insert, designated HD with a thermal insulation value of 1.05 clo (0.16 $m^2 \cdot K \cdot W^{-1}$), similar to the LD but with a thicker leather construction;

3) the standard US Army Three-Finger Shell with woolen insert, designated (AM) with a thermal insulation value of 1.46 clo (0.23 $m^2 \cdot K \cdot W^{-1}$).

b. ECWCS clothing items. The clothing worn by the subjects consisted of selected items shown in Table I with expedition-weight polypropylene underwear, The Temperate Battle Dress Uniform, the ECWCS standard parka and polyester liner, the standard US Army pile cap and the Personal Antiballistic System for Ground Troops (PASGT) helmet. The total thermal insulation value of this system was 3.6 clo. Additionally, the US Army Cold-Wet Vapor Barrier Boot (VBB) and the US Army Cushion-Sole Sock were worn on the feet by the subjects.

c. Subjects and Test design.

Laboratory experiments were conducted in an arctic climatic chamber at air temperatures set at 0, -20, and -30 °C (32, -4,-22 °F), relative humidity of 20-25 %rh, and wind speed of 1.0 m s^{-1} Six, healthy young male soldiers, unacclimated to cold, were used as subjects (Table II). Prior to any experimental testing, the subjects were given a health examination and became familiar with all exercise and test procedures. Body composition was determined by a conventional hydrostatic weighing technique (12). Maximal aerobic power (VO_2max) was initially determined on each subject using a treadmill test employing a continuous progressive intensity method (17,26). This parameter allowed the calculation of the relative work intensity of each subject on the four-man treadmills we used which can only operate at one speed at a time. Since steady-state internal temperatures (11,17,24,26) are tightly correlated to the percentage of maximum aerobic power of each person, statistical data base relationships can be developed between this dependent variable and core temperatures for a wide number of subjects in the future to arrive at environmental zones where the ECWCS and various handwear items are best or least protective at a given %VO_2max.

Upon arrival to the laboratory, each subject was weighed nude on a sensitive (± 10 g) electronic balance and instrumented with a rectal probe inserted 10 cm beyond the anal sphincter, skin thermistors, and ECG electrodes. For measuring average skin temperature, ten regionally placed skin sites were used in conformity with the original Quartermaster Research Engineering Center (QREC) harness sites (3) consisting of the following weighting of specific site temperatures:

T_{sk} (°C)= 0.15 × calf + 0.125 × upper thigh + 0.125 × inner thigh + 0.125 × kidney area + 0.125 × chest + 0.10 × cheek + 0.07 × upper arm + 0.07 × lower arm + 0.06 × hand + 0.05 × upper foot. This weighting formula was used to compare the original QREC database values compiled for the Standard A Arctic Uniform. Additionally, sites were measured with thermocouples placed on one hand at the tip of the middle finger as was the tip of the big toe on one foot (19,20).

Heart rate was obtained from the electrocardiogram measured continuously using chest electrodes (CM 5 placement) interfaced to a telemetry system (Hewlett-Packard 78510A &B).

After the subjects were prepared for the experiments, they dressed in the respective ensemble for the day and then had their dressed weight recorded with the electronic balance outside an antechamber. The subjects then entered the arctic climatic chamber and had their skin and rectal probe leads connected for continuous on-line computer monitoring. The subjects then rested on a standard wooden bench for 15 minutes of baseline data at a given air temperature. After the initial period the subjects either continued on in an inactive mode or began exercise for an additional two hours or until they were withdrawn because of rectal temperatures reaching ≤ 35 °C and/or finger-tip skin temperature ≤5 °C. These lower limits were justification for removal of a given subject from the test for that day. Oxygen uptake was

collected every 60 minutes staggered from subject to subject using the Douglas bag technique; heat production ($W \cdot m^{-2}$) was calculated from the respiratory parameters obtained and the DuBois surface area equation (19).

The inactive mode required that the subject sit on a wooden bench for 120 minutes and was designed to simulate situations which immobilizes military personnel (i.e. sentry duty, bivouac, inclement weather waiting situations,etc.) for any length of time.

The active mode included controlled metabolic activity of walking on a level treadmill at a pace equivalent to 1.34 $m \cdot s^{-1}$. This represents roughly a metabolic activity of from 3 to 4 mets (1 met = 100W),(ref 11). During all experiments, subjects were not allowed to open or ventilate the ECWCS by opening closures, zippers, etc. thereby serving to control against disparate variances in body temperatures and heat flow brought about by any subject tendencies or personal options to behaviorally thermoregulate. This would probably not hold true in field situations.

d. Statistics. Statistical evaluation included a repeated measures analysis of variance followed by a Tukey's post-hoc test. Where this was not possible due to unequal cell distribution because of subject premature attrition or excessive interaction between environment and ensemble or activity mode, a linear transformation of data was done and the data analyzed further. A stepwise multiple correlation analysis was used to determine predictive equations for endurance time with each ensemble. The independent variables used to evaluate the various handwear/ECWCS ensemble included the finger temperature,rectal and mean skin temperatures and the metabolic heat production as a function of the endurance time (ET,min) for each subject.

3. RESULTS

Tables III- V show the physiological responses averaged (± SD) over the final exposure times for the specific handwear worn with the ECWCS.

a. Endurance time (ET, min). These tables show that there were clear differences in the endurance times obtained from the subjects with the different gloves and at the different activity levels. Analysis of variance (by non-repeated measures) indicated an overall significant effect of air temperature ($F = 45.8$, $p < 0.001$) and activity mode ($F = 4.6$, $p < 0.013$). During the resting and exercise modes, at air temperature of 0 °C, ET approached the maximum 2-hour designated experimental cut-off. The HD glove-type worn in unison with the ECWCS during the resting mode gave the lowest ET at this air temperature in comparison to the runs with the LD and AM glove-ECWCS combinations. Albeit the HD glove has a slightly higher thermal insulation (1.05 clo, regional copper hand evaluation) compared to the LD glove because of an additional leather shell, this glove furnished minimal protection. It is entirely possible that the low middle finger skin temperatures observed (Table IV) with the HD-ECWCS combination were responsible for the lowered ET's. In fact, the results provided by linear transformation and further statistical evaluation of the data revealed that in the resting mode experiments, the T^{mf} observed in the AM-ECWCS combination experiments (Table V) were significantly higher ($P < 0.001$) than those with the HD and LD experimental runs.

Figures 1,2, and 3 combine the average ET and finger temperature responses plotted as a function of air temperature. These figures illustrate the marked decrease in ET. There was an constant decline in ET at each lowered air temperature. In the resting experiments, the AM-ECWCS combination showed the least gradual decline (evident by the slope of ET/T_a). During the resting mode experiments at -30 °C, the LD-ECWCS combination showed the lowest average ET's (ET= 25.5 ± 3.0 SD min) experienced by the subjects (Figure 1 and

Table III). Figure 2 also shows the dramatic drop in ET's observed during the exercise mode at -20 and -30 °C with the HD-ECWCS and AM-ECWCS combinations.

b. Middle finger temperatures (T_{mf}).

In general, the values shown for the 3rd finger nail bed skin temperature ≤ 5 °C (41 °F) were often the basis for early removal of the individuals from the experiment. Because of this, the repeated measures ANOVA was possible only with data obtained for all glove-ECWCS combinations at T_a= 0 °C. A non-repeated measures ANOVA was used on the substance of data obtained in the other air temperature-garment-activity combinations.

T_{mf} values were significantly different for each air temperature level (F= 35.9, P < 0.001) and activity mode (F= 148, P< 0.001). Pairwise significant differences of T_{mf} were demonstrated between the AM-ECWCS and LD-ECWCS combinations at 0 °C.

c. Ten-site mean weighted skin temperature (T_{sk}).

$\bar{T}_{sk}$ values were significantly different at each air temperature (Tables III-V) (F= 30.3, P < 0.005) and at each activity mode (F= 20.5, P< 0.005). In general, $\bar{T}_{sk}$ was lowest when the subjects were in the resting mode. There were no significant differences in the glove-type. This would be expected because $\bar{T}_{sk}$ is a thermoregulatory property representative of the heat flux at the "shell" of the body's surface area rather than signifying direct circulatory heat flow to the extremities which respond to an adrenergic neural drive (1,26,27,28). Nevertheless, in our experiments as if $\bar{T}_{sk}$ dropped below 30.9 °C as shown in experiments at T_a's - 20 °C and -30 °C (Tables III - V), subjective discomfort was quite pronounced. During these experiments when the $\bar{T}_{sk}$ was below this threshold (at T_a = -20 °C, $\bar{T}_{sk}$ = 28.9 ± 1.1 SD), individuals were visibly shivering.

d. Deep body (rectal) temperature (T_{re}).

T_{re} values, as expected, were significantly different between activity mode ($F= 127.2$, $P< 0.001$) (Tables III-V). At 0 °C, all glove combinations with the ECWCS maintained final T_{re} between 36.6-37.0 °C in the resting mode. The effect of glove type was not statistically significant ($F = 0.4$, $P = 0.68$). At each lower temperature, T_{re} dropped -0.2 °C for each 10 °C decrease in air temperature.

Characteristically, for continuous exercise, internal body temperature rises about 0.14 °C for each multiple above the resting state (11,17,24,26). For the data in the present study at 3 mets, this amounts to about 0.42 °C above baseline T_{re} at rest. Our data indicate almost a 0.20 °C rise in T_{re} for each multiple above 1 met with the ECWCS. This demonstrates a slight heat strain possible when the ECWCS is worn in the manner used in this study (i.e. completely closed configuration).

Since regulatory sweating is closely associated with absolute heat production and mean body temperature (11,17,24), a requirement is that adequate evaporation be provided with the ECWCS. At 0 °C in our study, maximal weight loss due to sweating was at 280 $g \cdot h^{-1}$ which resulted in an estimated skin wettedness (10) under clothing of close to saturation (0.80 to 1.00). The result was a slightly elevated T_{re} at 0 °C, visibly damp polypropylene underwear and fiberpile layers and near saturation of the inner nylon taffeta lining of the Gore-Tex® parka.

e. Mean body temperature (T_b) and Level of Heat Debt (kJ).

Mean body temperature is often modelled (6,7,11) as composed of two nodes or compartments: a deep mass at the core (T_{re}) and a shell mass represented by mean skin temperature. The mass represented by the core temperature (α) shrinks from 89% of the body in warm temperatures to about 67% of the body or lower. Since the relative proportions

[α;(1-α)] vary as a function of ambient temperature and activity, T_b very conveniently predicts the level of heat debt and cold stress (or level of discomfort, i.e ref 16).

Figure 4 shows a plot of the mean body temperature as a function of air temperature calculated from the respective $\bar{T}_{sk}$ and T_{re} values obtained in this study. The weighting used for T_b in this analysis was $0.2 \cdot \bar{T}_{sk} + 0.8 \cdot T_{re}$. The data show the dramatic drop in level of mean body temperature during the resting experiments which were significantly lower than in the exercise runs ($P < 0.001$). The subtle decline in T_b level is also shown for the exercise runs with a significant difference in T_b apparent at -30 °C ($P < 0.05$). This figure also demonstrates that T_b may also be a better estimator or guide for subject withdrawal from the cold (along with T_{mf}) than rectal temperature levels per se. For example, in our study (Table IV) the HD-ECWCS combination during exercise at -30 T_a revealed an average T_{re} of 37.5 °C ± 0.22 SD but a $\bar{T}_{sk}$ of 28.9 °C and a T_{mf} of 16.3 °C. These temperatures translate to a mean body temperature of 35.8 °C (Figure 4) which shows excessive cold discomfort.

Table VI represents the average level of heat debt (in kJ) that the subjects were in during the respective exposures. This parameter was calculated from the T_b changes in comparison to a set temperature T_{bo} = 36.3 °C which is evident, for the most part, when T_{re} = 37.0 °C and $\bar{T}_{sk}$ = 33.5 °C (11,17).

The level of heat debt {δS, kJ} may be expressed by

$$\{\delta S\} = c_b \cdot m_b \cdot [T_b - T_{bo}], \quad \text{kJ} \qquad (1)$$

where,

c_b = the body specific heat constant, 3.475 $kJ \cdot (kg \cdot K)^{-1}$

m_b = body weight, kg

T_{bo} = ideal mean body temperature at thermo-neutrality.

The table confirms the observations detailed before attributed to the disparate heat flux from the extremities (e.g. T_{mf}) found in the experiments with the specific glove-ECWCS configurations (Figures 1-3). An overall change in level of body heat content of about -243 kJ (e.g. -58 kcal) is generally associated with a drop of T_b (from thermoneutrality) of 1 °C. Typically, the change in heat content of -104 kJ is attributed as uncomfortable. A decreased level of heat content of -630 kJ is considered intolerable. The latter represents a drop of 2.6 °C in mean body temperature which was not observed in this study with the ECWCS with any glove.

f. Multiple Correlation Analysis.

A stepwise multiple correlation regression analysis was used to evaluate the data further for prediction of ET as a function of the critical physiological responses. The best prediction equations obtained for each glove-ECWCS combination were:

LD-glove ET (min)= $3.44(T_{mf}) - 0.17(M) - 4.81(T_{re}) + 1.01(\bar{T}_{sk}) + 198$, [$R^2 = 0.68$; $P < 0.004$]

HD-glove ET (min)= $3.90(T_{mf}) - 0.14(M) - 23.8(T_{re}) - 2.50(\bar{T}_{sk}) + 1001$ [$R^2 = 0.70$; $P < 0.001$]

AM ET (min)= $2.01(T_{mf}) - 0.19(M) - 6.44(T_{re}) + 1.94(\bar{T}_{sk}) + 264$ [$R^2 = 0.73$; $P < 0.006$]

4. DISCUSSION

It is generally recognized that human performance in extreme cold is provided by the person's ability to maintain thermal balance (11). During exercise or inactivity, the body exposure in the cold is limited by time, ambient temperature, and wind speed (2,3,4,5) and the body often loses heat faster than it can produce it. The lower limits of a person's ability to regulate internal body temperature is set when the metabolic heat flowing to the skin surface can no longer equal the heat loss from the skin surface. By vasoconstriction of the peripheral blood vessels the insulation of the body's skin layer can be changed by a value equivalent to wearing a light sweater (11). The extension of the lower thermal limits can be done by the addition of more clothing with a higher thermal resistance and by actively exercising for a limited period of time and intensity. Since homeotherms control body temperature by energy exchange, energetics plays an important role in the responses to cold stress. Coupled with the capacity to elevate and sustain metabolism and improve insulative properties are the interactions between physiological systems governing each response (14). Often these responses in their attempt to defend homeostasis act contrary to each other. For example, effector drive via vasomotor activity occurs primarily in the skin vessels where there is a high degree of vasoconstrictor tone: the hands and the feet. Alpha-constrictor receptors predominate in the skin vessels which are supplied with rich sympathetic adrenergic fibers; vasodilation occurs primarily at these sites by decrease in the vasoconstrictor tone solely and once a set lower temperature at the sites is reached, it is very difficult to improve circulatory heat flow to them (7,13,14,17,27,28). Van Dilla (27) estimated that circulatory heat flow to the fingers and toes in a person comfortably warm at rest (i.e. physiologically "thermoneutral") is about 100 ml• min^{-1} but drops to less than 1 ml• min^{-1} during vasoconstrictor activity (during exercise and/or cold stress). Added to these responses is the complication governed by the biophysics of thin

cylinders (20). These sites have little mass (sparse muscle layers) and therefore limited passive heat content and a large surface area for heat loss compared to their mass. Coupled with this is the fact from physics (20,25) that if a cylinder or sphere is smaller than a given critical radius, adding additional insulation to it actually increases heat loss, so added layers to five-finger gloves are often no help in warding off cold stress. A necessity along with maintaining a comfortably warm body surface area is the fact that a sufficiently high localized temperature must be maintained in the hands and feet.

The multiple correlation analysis equations presented in the <u>Results</u> section were used in an attempt to develop a prediction equation which would be useful in estimation of endurance times based on the physiological responses (including finger temperature) of this study. Figure 5 shows ET plotted as a function of given intervals of finger temperature (T_{mf}) rather than air temperature because T_{mf} is considered the most potent independent variable governing performance in the cold. The figure lines were obtained by introduction of variables to equations garnered for the specific glove-ECWCS combinations. Finger temperature was the variable input to the separate equations obtained for rest and exercise. The following were assumed:

For rest:

T_{sk} = 33 °C, assumed as a comfortable level (11)

M = 65 W• m^{-2}, roughly 1.1 met suitable for guard duty

T_{re} = 37.0 °C, normal internal body temperature at rest

These levels were deemed as appropriate in keeping a person within the comfortable zone at air temperature of 0 °C with the glove-ECWCS from our results. The middle finger temperature was varied from 25 °C down to 5 °C in the simulation, the latter being the

threshold for extreme discomfort and the temperature level at which subjects were removed from the experiments in our study. Similarly, for light work intensity:

T_{sk} = 29 °C,

M = 175 W• m^{-2}, i.e 3 mets

T_{re} = 37.3 °C,

The latter set temperatures and metabolic heat production were set based on a wealth of data showing the average steady-state rectal and skin temperature are present with this M (11,16,24).

The interesting property of this simulation is the fact that the contribution of the forcing drive of finger temperature adds itself as a fine control to the ET as evident in the exercise mode. The ET is essentially offset during activity from the resting mode at each constant finger temperature level. For both the resting and exercise mode, the observations that the Arctic mitten-ECWCS combination provides the most elevated endurance times is supported by the results (Figure 3 and Table V) and anecdotal accounts (7,13).

This simulation shows that with exercise and ECWCS the ET becomes reduced in comparison to the rest activity as a function of finger temperature and suggests that the intrinsic insulation of the ECWCS was reduced by excessive moisture thereby reducing the efficacy of the garment. In our experiments subjects were not allowed to remove or open any of the exterior layers of the ECWCS. Many reports (7,23,29) indicate that wetting of the clothing reduces its intrinsic insulation.

This study could not provide information whether the inner layers of the ECWCS furnishes additional out-wicking of sweat during the higher metabolic activities which is an

interesting study to do in the future. However, the intermediate layers were excessively saturated with unevaporated sweat and individuals were in mild heat strain at 0 °C as evident by the rectal temperatures observed. Figure 5 serves as a useful guide that indicates that decreased performance (implicit with ET) is associated with critical thresholds of extremity skin temperatures. These should not be overlooked when other thermoregulatory variables are deemed optimum. Reduction of cold sensation at this site is a key factor in reducing casualties during cold stress. Other classical studies have addressed these problems before which continue to be the most vulnerable link to cold weather clothing (5,7,8,13).

In summary, our study indicates that, in general, the ECWCS used with various handwear items offers reasonable protection during cold stress and resting activity. The standard US Army three-finger Arctic Mitten Shell with woolen insert (AM) still provided the most prominent protection based on finger temperature responses during exercise when vasoconstrictor activity is pronounced. The ECWCS should tender adequate ET's in cold-dry ambients provided that ventilation and removal of extra layers of outer clothing is possible especially during heavy exercise in moderate cold zones (> 0 °C) when body sweating wets the inner layers. As shown by this study, ET's can indeed become lowered because of this occurrence and extremity temperatures become crucial in predicting exposure limits.

DISCLAIMER

TABLE I. CLOTHING COMPONENTS OF THREE PROTOTYPE ECWCS CLOTHING SYSTEMS*.

	ECWCS #1	ECWCS #2	ECWCS #3
head	balaclava PASGT helmet	balaclava PASGT helmet	balaclava PASGT helmet
feet	polypropylene socks cushion sole socks white vb boots	polypropylene socks cushion sole socks white vb boots	polypropylene socks cushion sole socks white vb boots
hands	extreme (arctic) cold weather mitten	extreme (arctic) cold weather mitten	extreme (arctic) cold weather mitten
upper torso	polypropylene shirt fiberpile cardigan 4 oz field coat liner Gore-tex parka®	polypropylene shirt fiberpile cardigan 6oz field coat liner Gore-tex parka®	polypropylene shirt fiberpile cardigan (wool shirt (og 108)) 4 oz field coat liner Gore-tex parka®
lower torso	polypropylene trousers fiberpile trousers 4 oz. field trouser liner;field trouser; Gore-tex® trousers	polypropylene trousers 6 oz. field trouser liner;field trousers; Gore-tex® trousers	polypropylene trousers 4 oz. field trouser liner field trousers; Gore-tex® trousers
I_T(clo)	3.83	3.87	3.42
I_m/clo	0.12	0.11	0.11
weight (kg)**	10.8	10.8	10.9

*evaluated on a USARIEM copper manikin (T_a=0°C,wind speed= 1.1 $m \cdot s^{-1}$,75 %rh; weights include standard vapor barrier boots (3.4 kg) and PASGT helmet (1.6 kg).

Table II. DESCRIPTIVE DATA OF SUBJECTS

AGE (years)	HEIGHT (cm)	WEIGHT (kg)	A_D m^{-2}	BODY FAT (%)	VO_2 max (ml min^{-1} kg^{-1})
24 (±4.9)	175 (±3.8)	68.8 (±11.1)	1.83 (±0.16)	15.62 (±7.11)	48.35 (±7.56)

N=6 SUBJECTS

Table III. Mean Final Values For Specific Physiological Responses During Rest and Exercise with the ECWCS and Specific Handwear Items.

ECWCS with specific glove	Variable	0°C		-20°C		-30 °C	
		Means	SD	Means	SD	Means	SD
LD	ET (min)	116	± 9.7	62	± 37.0	25.5	± 3.0
{Sit mode}	T_{mf} (°C)	12.5	± 0.81	7.9	± 1.9	6.9	± 2.7
	$\bar{T}_{sk}$ (°C)	31.1	± 0.93	29.3	± 1.8	29.2	± 0.7
	T_{re} (°C)	36.7	± 0.35	36.6†	± 0.76	37.1#	± 0.31
	M ($W \cdot m^{-2}$)	66.9	± 9.83	69.0	± 11.2	88.0	± 12.7
	HR ($b \cdot min^{-1}$)	69.8	± 6.84	68.4	± 11.7	69.0	± 8.6
LD	ET (min)	115	± 11.9	111	± 22.0	---	---
{Exercise mode}	T_{mf} (°C)	31.5	± 2.4	21.1	± 8.1	---	---
	$\bar{T}_{sk}$ (°C)	32.7	± 0.5	31.0	± 0.8	---	---
	T_{re} (°C)	37.6	± 0.16	37.6	± 0.10	---	---
	M ($W \cdot m^{-2}$)	168.8	± 7.3	168.5	± 10.5	---	---
	HR ($b \cdot min^{-1}$)	92.3	± 11.2	93.7	± 8.5	---	---

[1] LD Clo value = 0.86 clo; † = 5 subjects only; # = 4 subjects only; ... no data.

Table IV. Mean Final Values For Specific Physiological Responses During Rest and Exercise with the ECWCS and Specific Handwear Items.

ECWCS with specific glove	Variable	0°C		-20°C		-30 °C	
		Means	SD	Means	SD	Means	SD
HD[a]	ET (min)	108	± 16.7	62.0	± 31.0	45.0	± 43
{Sit mode}	T_{af} (°C)	11.3	± 2.3	8.7	± 2.8	7.0	± 1.8
	T_{sk} (°C)	30.9	± 1.0	28.9	± 1.1	29.2	± 2.1
	T_{re} (°C)	36.6	± 0.43	36.9	± 0.42	37.0†	± 0.38
	M ($W \cdot m^{-2}$)	59.8	± 11.5	60.0	± 13.4	64.1	± 21.8
	HR ($b \cdot min^{-1}$)	65.5	± 6.8	66.2	± 7.5	81.4	± 11.3
HD	ET (min)	120	± 0	120	± 0	71.0	± 48
{Exercise mode}	T_{af} (°C)	29.0	± 3.4	28.2	± 3.4	16.3	± 9.4
	T_{sk} (°C)	32.7	± 1.0	30.5	± 0.9	28.9	± 2.2
	T_{re} (°C)	37.6	± 0.20	37.6	± 0.14	37.[illegible]†	± 0.22
	M ($W \cdot m^{-2}$)	163.7	± 12.0	174.4	± 14.0	169.4	± 14.3
	HR ($b \cdot min^{-1}$)	92.7	± 6.4	89.2	± 10.8	92.8	± 7.6

[a] HD Clo value = 1.05 clo on regional copper hand evaluation; † = 5 subjects only; # = 4 subjects only; ... = no data.

Table V. Mean Final Values For Specific Physiological Responses During Rest and Exercise with the ECWCS and Specific Handwear Items.

ECWCS with specific glove	Variable	0°C		-20°C		-30 °C	
		Means	SD	Means	SD	Means	SD
{Arctic mitten}[a]	ET (min)	120	± 0	81.0	± 25.0	...	...
{Sit mode}	T_{mf} (°C)	18.9	± 6.0	7.6	± 1.6	...	...
	†T_{sk} (°C)	31.2	± 0.8	29.1	± 1.6	...	...
	T_{re} (°C)	36.6	± 0.20	36.7	± 0.39	...	...
	M ($W \cdot m^{-2}$)	63.8	± 12.3	65.2	± 12.2	...	...
	HR ($b \cdot min^{-1}$)	63.2	± 6.3	65.7	± 7.9	...	...
AM	ET (min)	120	± 0	...	...	79.0	± 40
{Exercise mode}	T_{mf} (°C)	33.8	± 1.8	...	...	16.1	± 10.5
	†T_{sk} (°C)	32.7	± 1.4	...	...	29.8	± 1.0
	T_{re} (°C)	37.6	± 0.23	...	...	37.5	± 0.43
	M ($W \cdot m^{-2}$)	168.3	± 11.2	...	...	171.4	± 12.8
	HR ($b \cdot min^{-1}$)	94.5	± 7.1	...	...	96.0	± 12.6

[a] Arctic mitten(AM) Clo value = 1.46 clo on regional copper hand evaluation; † = 5 subjects only; # = 4 subjects only; ... = no data.

Table VI. LEVEL OF HEAT DEBT INCURRED WITH ECWCS & SPECIFIC HANDWEAR (kJ).

	Air Temperature		
	0°	-20 °C	-30 °C
LD-REST	-167.9	-278.4	-187.2
LD-EXERCISE	76.6	-4.8	(...)
HD-REST	-201.4	-240	-206
HD-EXERCISE	76.5	-28.9	-124.8
AM-REST	-187.2	-268.8	(...)
AM-EXERCISE	76.6	(...)	-67

(...) = no data; level of heat debt of -104 kJ is uncomfortable; -630 kJ (-150 kcal) is intolerable.

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FIGURE LEGENDS

Figure 1. Mean tolerance time (ET, min) plotted as a function of air temperature in the series of experiments with the light duty (LD) glove- ECWCS combinations.

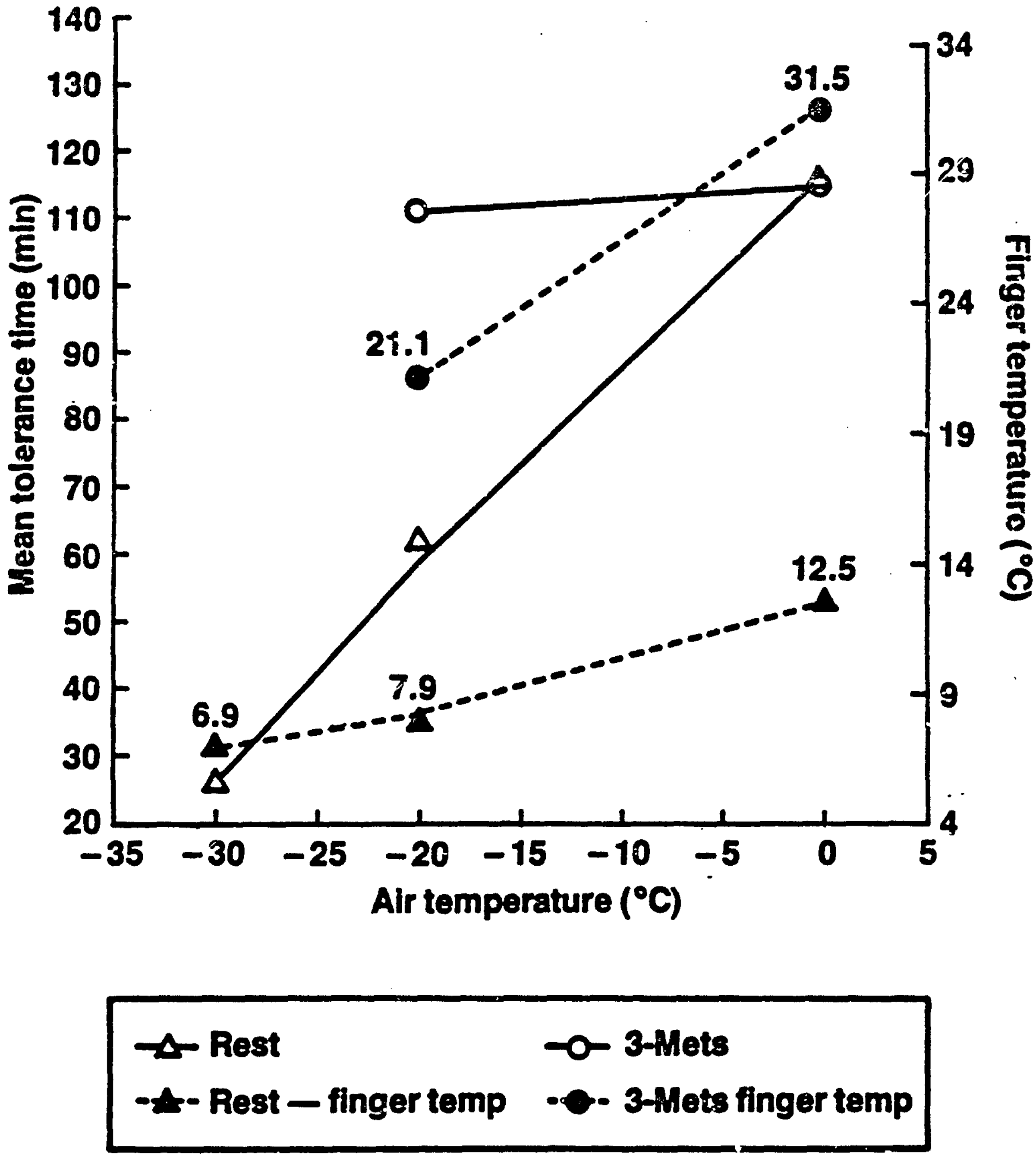
Figure 2. Mean tolerance time (ET, min) plotted as a function of air temperature in the series of experiments with the heavy duty (HD) glove- ECWCS combinations.

Figure 3. Mean tolerance time (ET, min) plotted as a function of air temperature in the series of experiments with the 3 finger Arctic Mitten Shell (AM)-ECWCS combinations.

Figure 4. Mean body temperatures $\{T_b = 0.2 \cdot T_{sk} + 0.8 \cdot T_{re}\}$ plotted as a function of air temperatures for all experiments.

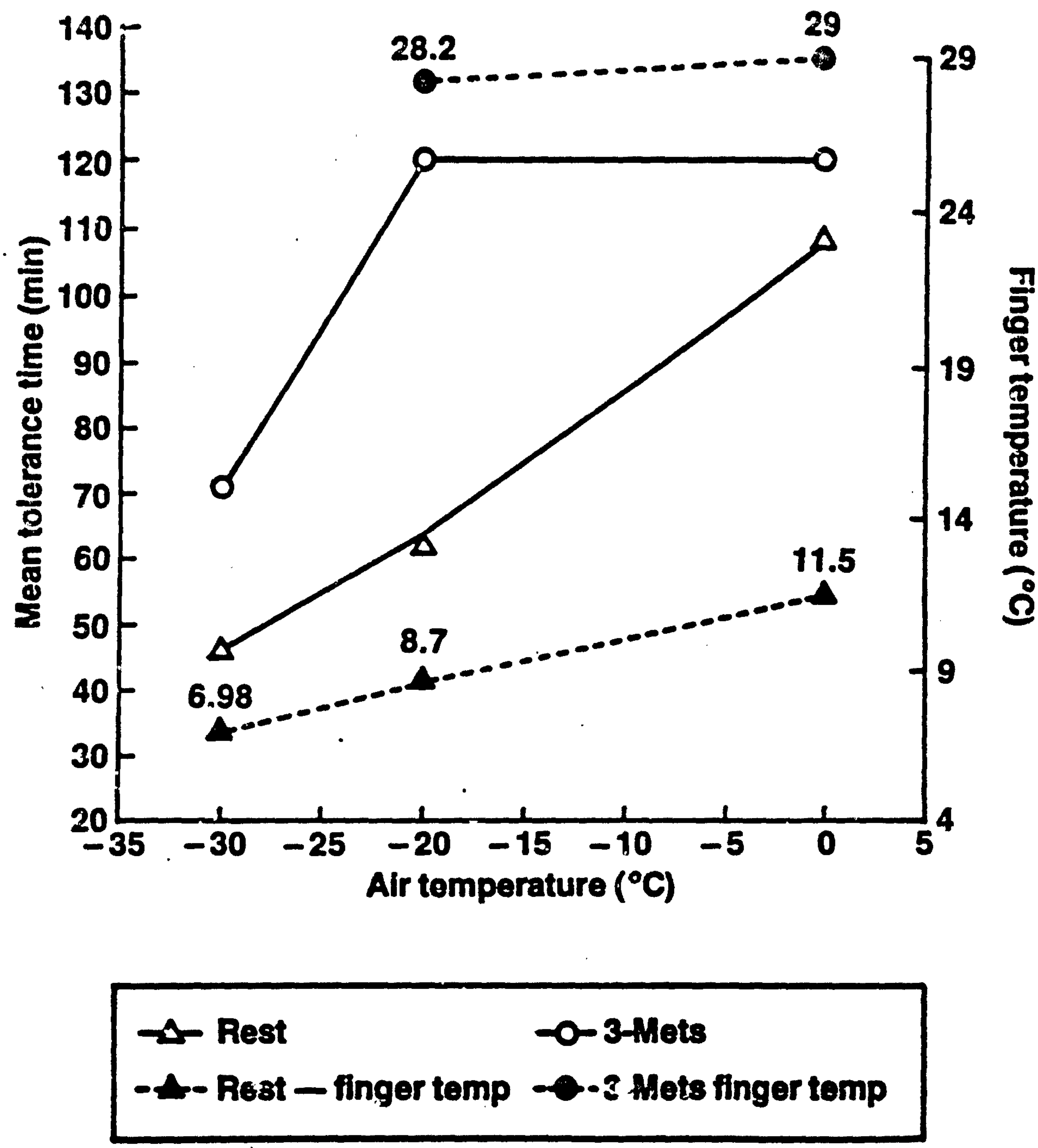
Figure 5 Prediction values for ET (min) as a function of finger temperatures from data garnered by a multiple correlation analysis.

LIGHT DUTY GLOVE (LD){.86 clo}
2-HR TEST WITH ECWCS



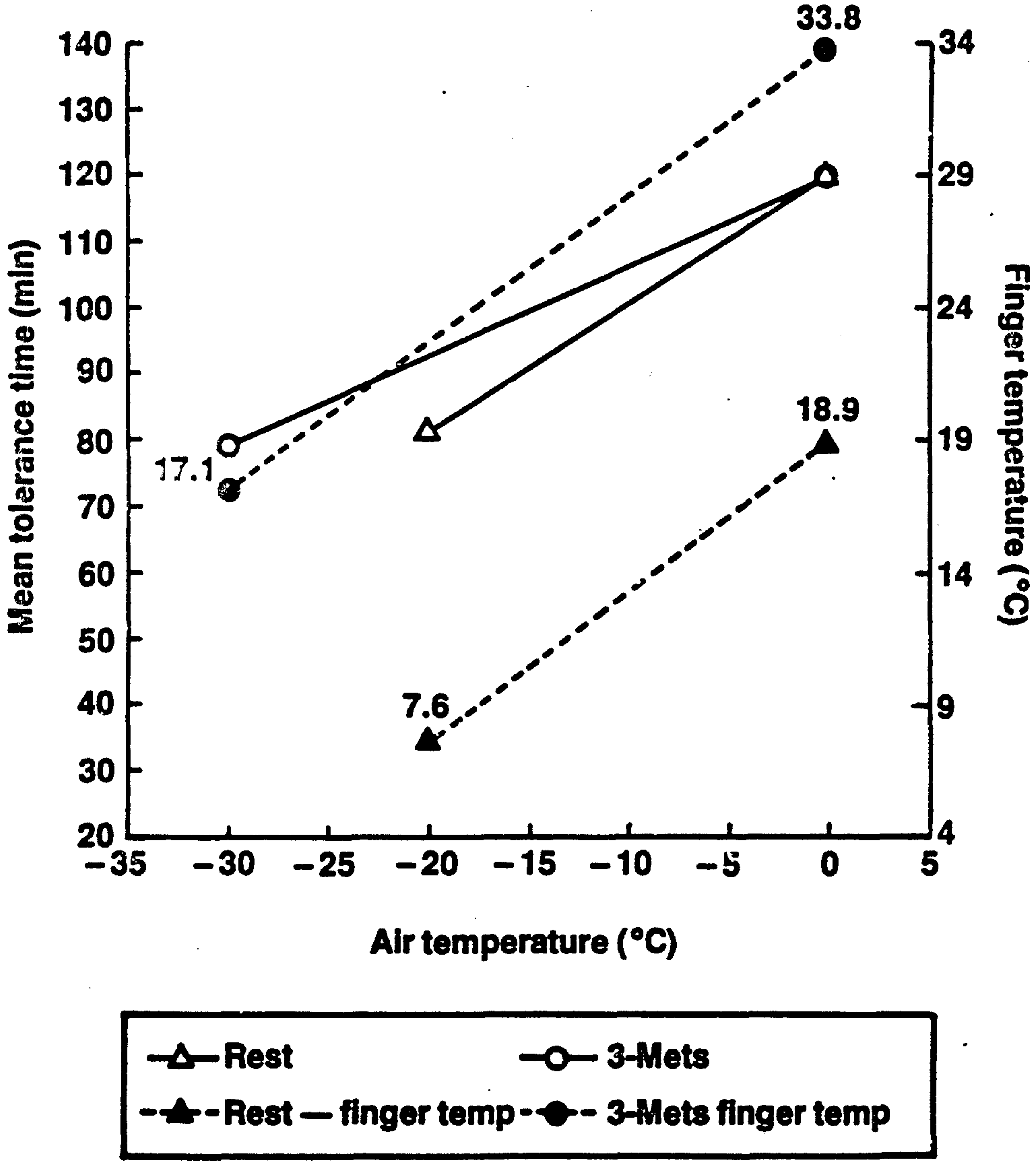
ECWCS insulation = 3.6 clo

HEAVY DUTY GLOVE (HD) {1.05 clo}
2-HR TEST WITH ECWCS

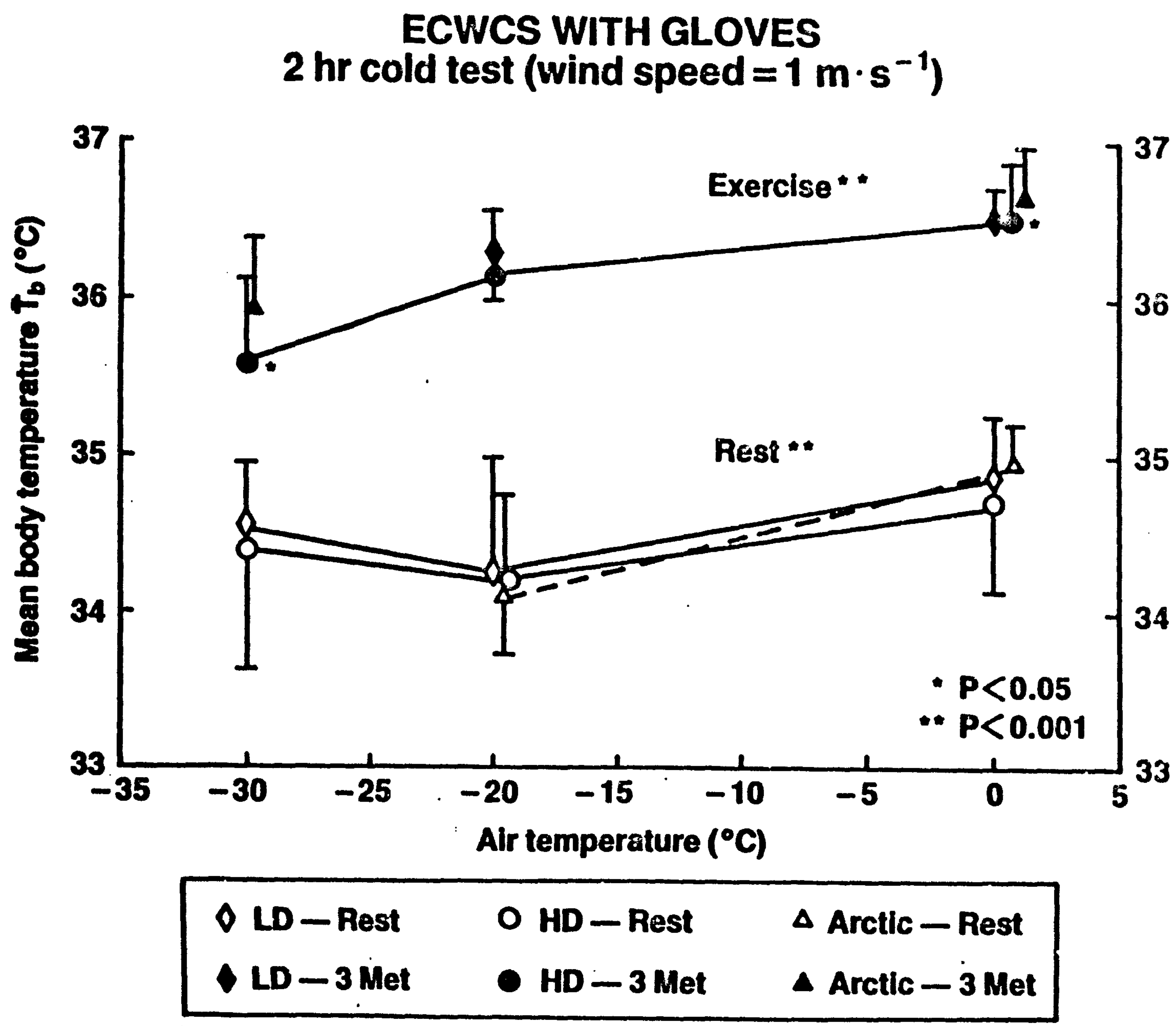


ECWCS insulation = 3.6 clo

ARCTIC (STD) MITT {1.46 clo}
2-HR TEST WITH ECWCS

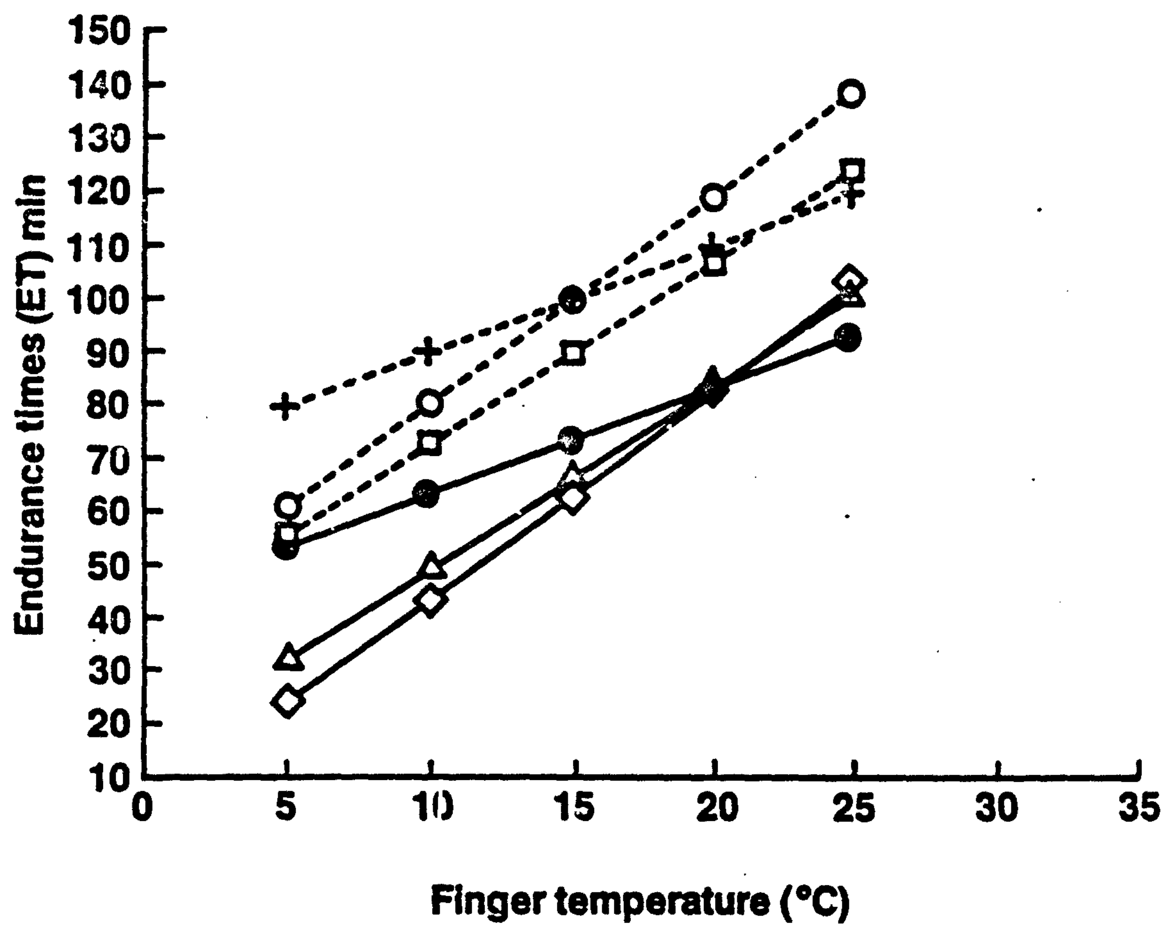


ECWCS insulation = 3.6 clo



ECWCS WITH GLOVES
2 hr cold test (wind speed = 1 m · s⁻¹)
Mean body temperature Tb (°C)
Air temperature (°C)
Exercise **
Rest **
* P<0.05
** P<0.001
LD — Rest
HD — Rest
Arctic — Rest
LD — 3 Met
HD — 3 Met
Arctic — 3 Met

PREDICTION VALUES FOR ET COLD TEST WITH ECWCS & SPECIFIC GLOVES



Rest & Ex (Met = M)

--□-- R - LD —△— 3M - LD --○-- R - HD
—◇— 3M - HD --+-- R - Arctic —●— 3M - Arctic

Based on stepwise multiple corr
$\{ET = b1T_{mf} + b2M + b3T_{re} + b4T_{sk} + intcpt\}$